BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B70 09090

SUBJECT: Study of the MSC Proposed NC1/NC2 Targeting Routine for Skylab Rendezvous - Case 610

DATE: September 30, 1970

FROM: C. O. Guffee
R. C. Purkey

ABSTRACT

An evaluation of the Skylab NC1 and NC2 rendezvous maneuver targeting method, as proposed to the Software Configuration Control Board on March 17, 1970, has been conducted. Two aspects were studied:

1. How well can the proposed modified CSI two-maneuver targeting method compute a three-maneuver sequence, and

2. How effective is the proposed correction for Keplerian propagation?

The study produced the following conclusions:

1. The modified CSI targeting method produces excellent results when compared to the solutions obtained by the conic NC/NH/NSR targeting method. This means that the approximations used in the modified CSI method are adequate for the Skylab rendezvous.

2. Conic targeting with the proposed correction for Keplerian propagation produced excellent solutions for the NC1 and NC2 maneuvers when compared to the precision-integrated solutions.

3. The NC1 maneuver in-plane delta-v can be in error by several ft/sec on either side of the ideal solution with no appreciable affect on the total delta-v required for rendezvous. Outside this range, one or more of the subsequent maneuvers will be retrograde and a significant delta-v penalty is possible. The conic targeting methods without the correction for Keplerian propagation can produce NC1 solutions which are near the edge of, but within, the no delta-v penalty range. Such a biased NC1 solution, together with expected navigation and maneuver execution errors, is likely to result in NC1 maneuvers outside the no penalty range.

4. An NC1 maneuver which is larger than the ideal causes the active vehicle to be further behind the target at NC2 and at NCC. This results in an increase in the slant range during the NC2 to NCC phase, so great, in some cases, that VHF tracking is not possible prior to the NCC maneuver.

Based on conclusions 3 and 4, it is recommended that a correction for Keplerian propagation be incorporated for the Skylab CSM on-board targeting routine for the NC1 maneuver.

BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B70 09090

SUBJECT: Study of the MSC Proposed NC1/NC2 Targeting Routine for Skylab Rendezvous - Case 610

DATE: September 30, 1970

FROM: C. O. Guffee
R. C. Purkey

MEMORANDUM FOR FILE

I. Introduction

A study of the MSC proposed on-board NC1/NC2 rendezvous targeting routine* has been performed to determine its effectiveness. Two separate problems were studied:

A. The accuracy of the proposed targeting routine as compared to a true NC/NH/NSR targeting routine when both routines use conic equations of motion, and

B. The accuracy of the proposed targeting routine as compared to an NC/NH/NSR targeting routine when the former uses conic equations of motion and the latter advances state vectors by integration with a non-spherical gravity model.

The first problem arises from the fact that the proposed on-board NC1/NC2 targeting routine uses some analytical approximations and the solution for a two-maneuver sequence to obtain the delta-v required for the first maneuver of a three-maneuver sequence. The second problem arises from the fact that the proposed routine uses conic equations of motion to approximate the true motion of the spacecraft in a non-spherical gravity field. In studying the second problem, MSC's proposed approximate correction to account for the errors due to Keplerian propagation was evaluated.

II. Proposed Skylab Rendezvous Profile

The proposed Skylab rendezvous profile consists of the sequence of events shown in Table 1. The target

---

*This is an evaluation of the Skylab rendezvous profile and targeting schemes as proposed to the AAP Spacecraft Software Configuration Control Board March 17, 1970 (see Reference 2).

SEQUENCE OF EVENTS DURING SKYLAB RENDEZVOUS

Event	No. Orbits of Coasting Flight Following Event	Resulting Orbit (n.m.)
Insertion	Minimum of (M-3.5, 3.5)	(81 x 120)
NC1 Maneuver	Maximum of (1.5, M-5.5)	(120 x 95) to (120 x 215)
NC2 Maneuver	1/2 orbit plus 15 degrees	(215 x 95) to (215 x 215)
NCC Maneuver	1/2 orbit less 15 degrees	(215 x 225)
NSR Maneuver	1/2 orbit or less	(225 x 225)
TPI Maneuver	130 degrees of travel of target orbit	(225 x 237.5)
TPF Maneuver	----	(235 x 235)

TABLE 1

vehicle is in a 235 nm circular orbit, and the active vehicle is inserted at perigee of an 81 x 120 nm orbit. The total number of orbits from insertion to completion of rendezvous is a function of the phase angle that exists at insertion. This study will consider all M numbers* from 4 to 16. Reference (1) presents a study of SL-2 launch opportunities, and shows the phasing capability obtained as a function of M.

Figure 1 shows the proposed Skylab rendezvous profile for M=4. The figure shows the relative motion of the active vehicle with respect to the passive vehicle in local vertical, curvilinear coordinates centered in the passive vehicle. The horizontal axis lies along the passive orbit and the relative position of the active vehicle with respect to the passive vehicle is given by its distance behind and its differential altitude. Distance behind is the product of the radius of the passive vehicle and the phase angle between the two vehicles. The differential altitude is simply the difference in the altitudes of the active and passive vehicles. These quantities are positive for the active vehicle below and behind the passive vehicle.

NC1 and NC2 are phasing maneuvers, and NCC is a corrective combination maneuver designed to insure on-time arrival at the desired NSR conditions. NSR, TPI, and TPF are the standard Apollo coelliptic, Terminal Phase Initiation, and Terminal Phase Finalization maneuvers.

III. Targeting the Skylab Rendezvous Maneuvers

The only major new rendezvous targeting routine required for the Skylab CSM computer is the NC1 and NC2 targeting routine. Apollo Guidance Computer routines for targeting the NSR, TPI, and TPF maneuvers have already been developed for Apollo, and will be directly usable for Skylab. There is a requirement for a targeting routine for the NCC maneuver, but the only new coding to be developed involves a routine to establish the target vector required for the already available precision offset Lambert aim-point routine.

Both the NC1 and the NC2 maneuvers can be targeted as the first maneuver of th NC/NH/NSR three maneuver sequence. Thus, only one new targeting routine is required,

---

*The M number notation denotes the orbit number of the active vehicle at which rendezvous is obtained. The counter M is initialized to 1 at first apogee of the active vehicle.

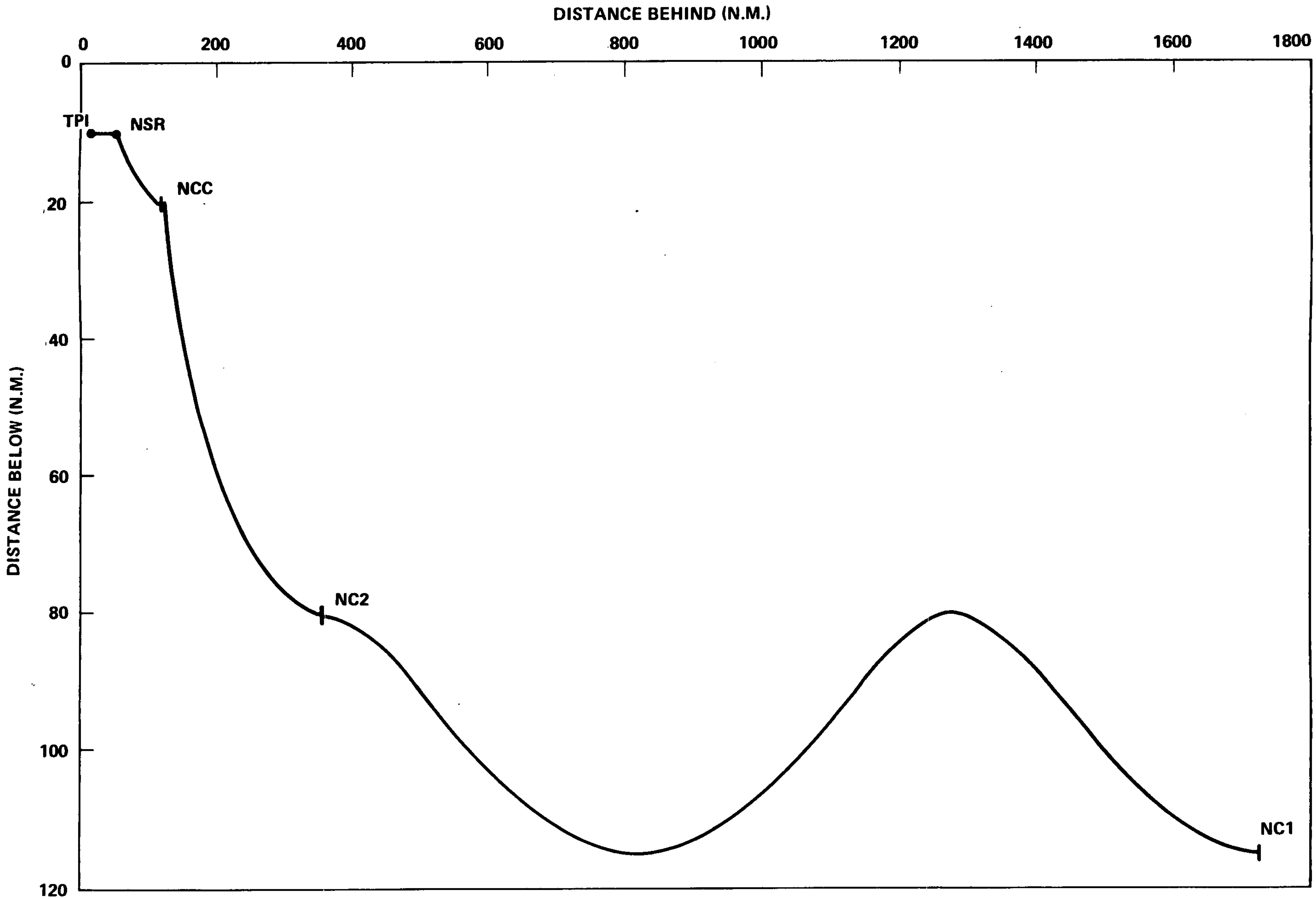

FIGURE 1 - THE PROPOSED RENDEZVOUS PROFILE FOR SKYLAB

and the input parameters to the routine are changed according to the maneuver being computed. MSC proposes using some analytical approximations and the solution to the CSI/CDH two-maneuver sequence to compute the NC1 and NC2 maneuvers. The method is discussed in Reference (2), and the authors' version of the Apollo CSI/CDH targeting routine was accordingly modified for this study. This targeting method will be referred to as the modified CSI method in the remainder of this memorandum. This method uses conic equations of motion when advancing the active and passive states. The terminology "true conic method" is used in this memorandum to designate the targeting method which considers the complete NC/NH/NSR sequence.

There is an inherent error in the solution produced by a targeting routine that assumes conic equations of motion. This problem is discussed in Reference (8) where it is shown that the magnitude of the error is primarily a function of the latitudes of the active and passive vehicles at the time the maneuver is to be performed. MSC has proposed a simple method of correcting for this error, and it is discussed in References (2) and (8). The proposed correction was studied with both the modified CSI and the true conic NC/NH/NSR targeting methods. The methods will be referred to as corrected or uncorrected according to whether or not the proposed correction is used. The effectiveness of the correction is to be evaluated.

In order to have a basis for comparison of the NC targeting methods, another NC targeting routine which uses precision integration for state vector propagation was used. This routine will be called the "precision NC/NH/NSR" method and is discussed in Reference (5).

The authors' versions of the NCC, NSR, and TPI targeting routines were also required for the study. These routines are discussed respectively in References (6) and (3), and are representative of the on-board targeting routines. These routines use precision integration and a non-spherical gravity model when advancing the state vectors.

IV. Outline of the Study

The study was started by establishing reference trajectories for minimum, maximum, and average phase angle differences at NC1 for each M number from 4 through 16. At each maneuver event of the reference trajectory, the location of the active vehicle with respect to the target vehicle and the delta-v required for the maneuver were recorded. The reference trajectory maneuvers were computed using the precision NC/NH/NSR method for the NC1 and NC2 maneuvers and the NCC/NSR and TPI routines for those respective maneuvers. These maneuver delta-v's will be referred to as the reference solution.

Next, actual trajectories were computed using the proposed on-board targeting methods. Again, at each maneuver point the location of the active vehicle with respect to the target vehicle and the maneuver delta-v's were recorded. In this way the resulting actual trajectories could be compared to the reference trajectories in terms of the relative position dispersions at each maneuver event and the delta-v requirements. A comparison of the dispersions in relative position at events, rather than at the same value of time, it necessary because the time of occurrence of events such as NC2 and NCC will not necessarily be the same for the reference trajectory and the actual trajectory.

Two actual trajectories were computed for each reference trajectory. One was obtained by using the corrected modified CSI method and the other by using the uncorrected modified CSI method. At the NC1 and NC2 maneuver points, the actual trajectory targeting problem was also solved using the precision NC/NH/NSR and the true conic NC/NH/NSR targeting methods. These solutions were not implemented, but were obtained to compare with the modified CSI solutions. The NCC, NSR, and TPI maneuvers were computed using the same routine used for the reference trajectories.

The states for the actual trajectories at NC1 were the same as the reference trajectory states, the deviations thereafter are due to the difference between the reference maneuver delta-v's and the actual maneuver delta-v's. All maneuvers were implemented impulsively. The states at NC1 were selected to be representative of the states that will exist for the actual Skylab mission. The active state at NC1 was at about -40 degrees latitude, in a 50° inclination orbit, and moving in a southerly direction. The passive state was ahead of the active vehicle by the required phase angle. The two orbits were initially coplanar, but would exhibit a small wedge angle by the time of the NCC maneuver due to the different precession rates. The NCC and NSR maneuvers correct the planar problem; however, for this study the out-of-plane components of delta-v at NCC and NSR were not included in the delta-v requirements. All other maneuvers have only in-plane components of delta-v.

V. Simulation Results

Test cases were run for minimum, average, and maximum phasing conditions for each M number from 4 through 16. A comparison of the corrected and uncorrected actual trajectories with the reference trajectory for the average phasing condition will be presented to illustrate the general conclusions obtained from the study. Generally, the average phasing condition cases adequately illustrate the results of the study. Some examples of minimum and maximum phasing cases will be presented to amplify certain points.

Figure 2 shows an expanded plot of the portion of the Skylab rendezvous from NC2 to TPF. The figure is taken from Reference (7) and shows the relative position of the reference trajectory for all three phasing cases. The reader should refer back to this plot during the remainder of the discussion of relative position errors at NC2 and NCC in order to fully understand the extent of the errors.

Two points must be made clear before giving the simulation results. The first is that the proposed rendezvous profile is not a delta-v optimum profile because of the use of the NCC maneuver. If all maneuvers from NC1 through NSR were performed as horizontal delta-v's at an apsidal crossing,* then the total delta-v from NC1 through TPI would be about 460 ft/sec for the reference trajectory. However, it is possible that the NCC maneuver will not be directed along the velocity vector and thus will be a non-optimum maneuver. The delta-v's required for the Skylab reference profile are about 460, 480, and 490 ft/sec respectively for the minimum, average, and maximum phasing cases.

The second point is that the delta-v differences between the actual maneuvers and the precision computed maneuvers must not be examined as a percentage error. The actual numerical difference between the two solutions is the important parameter. For example, the precision NC1 maneuver solution is on the order of 23 ft/sec for a maximum phasing case and 234 ft/sec for a minimum phasing case. An error of +12 ft/sec in either case produces about the same differential altitude ($\approx$7 nm) and downrange errors at NC2 ($\approx$16 nm per orbit of coasting flight) when compared to the respective reference trajectories.

---

*This is assuming all maneuvers from NC1 through NSR increase the energy of the orbit. This point will be discussed in more detail.

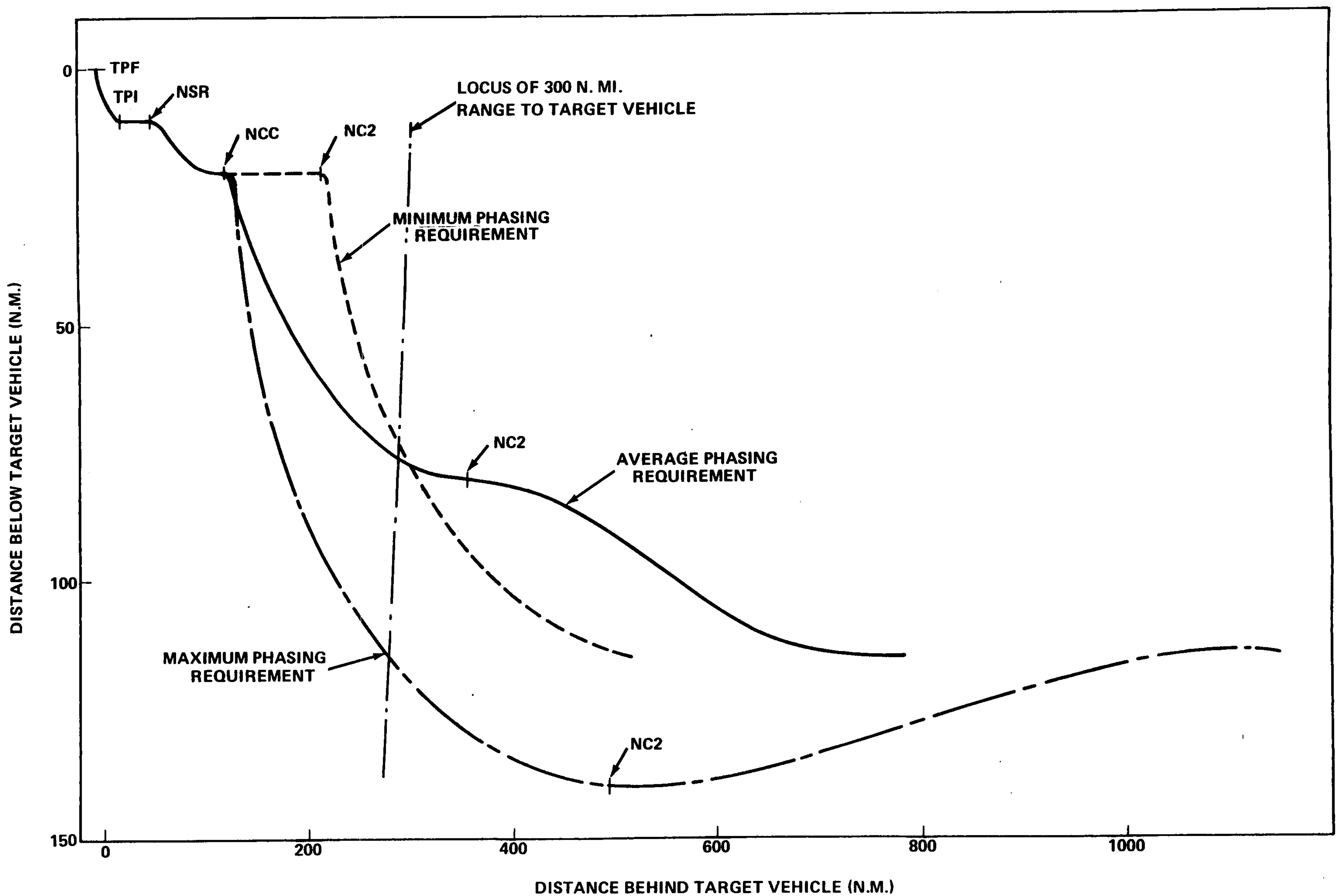

FIGURE 2 - RELATIVE MOTION PLOT OF FINAL PORTION OF SKYLAB RENDEVOUS TRAJECTORY

An important, though not surprising, early conclusion is that the modified CSI targeting method produces excellent results when compared to the true conic NC/NH/NSR method. The differences were generally on the order of 0.5 ft/sec, and the maximum error was less than one ft/sec. This was true regardless of whether or not both routines used the correction for Keplerian propagation. In other words, the approximations used in the modified CSI targeting method are quite good for the range of rendezvous trajectories of interest to Skylab. For this reason, no test results comparing the solutions obtained by the two methods will be given. Instead, all test results will compare the modified CSI solutions to the precision NC/NH/NSR solutions.

Table 2 shows the NC1 solutions for the reference trajectories where the precision targeting routine is used, and for the actual trajectories where the modified CSI routine is used. The modified CSI solutions are shown both with and without the correction for Keplerian propagation. The state vectors for the reference trajectories and for the actual trajectories were identical at the NC1 targeting point, and so the precision solutions for the actual trajectories are the same as the reference trajectory solutions. The delta-v's for the reference trajectories are all about the same value because approximately the same (average) phasing conditions exist for each M number.

It is seen that the actual delta-v's, when using the correction for Keplerian propagation, agree very closely with the precision solutions; however, the actual delta-v's, without the correction, vary considerably, reaching a maximum error at M=14. In Reference (8), it is shown that the error is primarily a function of the difference in the active and passive vehicle latitudes The latitude of the active vehicle is fixed at about -40 degrees for all NC1 cases; however, the latitude of the target vehicle varies with M.* The maximum NC1 targeting error will result when the target vehicle is nearest zero latitude. This is the situation for M=14.

---

*The latitude of the target vehicle varies from about -50 degrees for M=4 to about +23 degrees for M=16 for the average phasing case.

M	Modified CSI Solution (ft/sec) With Correction for Keplerian Propagation	Reference Solution (ft/sec)	Modified CSI Solution (ft/sec) Without Correction for Keplerian Propagation
4, 5, 6, 7	131.7	132.3	125.5
8	132.6	132.2	126.3
9	132.4	131.4	128.6
10	131.8	130.7	132.3
11	130.9	130.1	136.6
12	129.9	129.6	140.2
13	129.9	129.6	142.7
14	130.0	129.9	143.4
15	130.1	130.5	142.2
16	131.0	131.3	139.4

TABLE 2. DELTA-V SOLUTIONS AT NC1 FOR AVERAGE PHASING REQUIREMENTS

Table 3 shows the actual trajectory position errors at the NC2 maneuver event. The errors are the differences between the relative positions of the actual trajectory's NC2 locations and the reference trajectory's NC2 locations measured relative to the target vehicle at the NC2 event. For average phasing conditions, the reference trajectory NC2 maneuver point is located about 80 nm below and 350 nm behind the target vehicle (in the coordinates of Figure 2). If, for a particular case, the actual delta-v at NC1 (shown in Table 2) is larger than the reference delta-v, then the actual trajectory will have a higher altitude, and hence a smaller differential altitude at NC2. This will result in a negative error in differential altitude. Similarly, the catch-up rate of the actual trajectory will be slower than for the reference trajectory, thus the actual trajectory will lag the reference trajectory and result in a positive error in downrange distance at NC2. The reverse is true when the NC1 delta-v is smaller than it should be.

From Table 3 it is seen that the downrange position error at NC2 can be significant if the correction for Keplerian propagation is not used at NC1. For the average phasing case, the reference trajectory phase angle between the active vehicle and the target vehicle at NC2 is about 5.5 degrees. The phase angle at NC2 for the actual trajectory without the Keplerian correction at NC1 is on the order of 10 degrees for the worst case error (M=14). The corrected Modified CSI solution at NC1, however, produces small position errors at NC2.

Computed NC2 delta-v's for the reference trajectory and for the corrected and uncorrected actual trajectories are shown in Table 4. Since the actual trajectory NC2 locations are different from the reference trajectory locations, the precision NC2 solutions for the actual trajectories are also shown. Two points become apparent upon examining the delta-v's for the corrected actual trajectories. First, the precision solution is in close agreement with the reference solution, and second, the corrected modified CSI solution is in close agreement with the precision solution. The first agreement is simply because, as indicated in Table 3, the corrected NC1 solution achieves the NC2 position very well. The second agreement indicates that the corrected NC2 solution also models the real world very well.

Examination of the delta-v's at NC2 for the uncorrected actual trajectories shows that, first, the difference between the precision solution and the reference solution varies as a function of the M number, and second,

M	ERROR IN POSITION AT NC2 EVENT (Relative Position of Actual Trajectory - Relative Position of Reference Trajectory)			
	With Correction for Keplerian Propagation at NC1		Without Correction for Keplerian Propagation at NC1	
	Error in Differential Altitude (nm)	Error in Downrange distance (nm)	Error in Differential Altitude (nm)	Error in Downrange Distance (nm)
4, 5, 6, 7	0.13	-0.93	3.8	-26.8
8	-0.48	4.6	3.3	-38.1
9	-0.66	10.8	1.6	-26.5
10	-0.70	14.9	-0.93	19.7
11	-0.52	13.5	-3.6	93.8
12	-0.24	7.9	-6.0	181.4
13	-0.0050	0.53	-7.5	259.4
14	0.15	-5.0	-7.8	303.5
15	0.19	-7.1	-6.7	294.5
16	0.14	-4.7	-4.7	225.4

TABLE 3 Resulting Errors at NC2 Due to NC1 Targeting
(Reference trajectory is 81 nm below
and 350 nm behind target vehicle)

M	With Correction for Keplerian Propagation		Reference Trajectory Solution (ft/sec)	Without Correction for Keplerian Propagation	
	Modified CSI Solution (ft/sec)	Precision Solution (ft/Sec)		Modified CSI Solution (ft/sec)	Precision Solution (ft/sec)
4, 5, 6, 7	168.7	169.2	168.8	181.8	179.7
8	167.1	167.7	169.7	184.5	186.6
9	165.0	165.6	170.1	178.7	180.9
10	163.1	163.7	169.8	159.4	161.7
11	162.9	163.4	168.8	128.3	131.0
12	164.1	164.6	167.7	92.1	95.2
13	166.2	166.7	166.9	60.4	63.9
14	168.3	168.8	166.9	43.3	47.0
15	169.8	170.3	167.5	48.4	51.9
16	170.1	170.6	168.5	77.6	80.8

TABLE 4. DELTA-V SOLUTIONS AT NC2

there is good agreement between the uncorrected Modified CSI solution and the precision solution. The first is because, as indicated in Table 3, different phasing problems are being solved at NC2 for the reference and for the actual trajectory. Again, this phasing error is due to using the uncorrected NC1 solution. The agreement between the uncorrected Modified CSI and the precision solutions at NC2 is due to the fact that unlike the NC1 targeting problem, the latitude of the target vehicle at NC2 is about the same for all M numbers and is close to the latitude of the active vehicle. Hence, the inherent error in an uncorrected conic solution is small.

Table 5 shows the resulting phasing errors at NCC for the corrected and uncorrected actual trajectories. The error is computed in the same way as for Table 3. The reference trajectory is about 20 nm below and 120 nm behind the target vehicle at the NCC event. Again, the conclusion from Table 5 is that with the correction for Keplerian propagation, the actual trajectory is very close to the reference. However, without the correction, the error can be significant and for M numbers greater than 9, the positive downrange position errors have a secondary deleterious effect. The amount of on-board VHF tracking prior to the NCC maneuver is reduced because of the 300 nm limit on VHF tracking. In the worst case (M=14) the NCC maneuver occurs at about the 300 nm range, thus no VHF range data at all would be available to support this maneuver.

Table 6 summarizes the delta-v requirements at NCC and NSR, and gives the total delta-v required from NC1 through TPI for the reference trajectories and for the uncorrected actual trajectories. The NCC maneuver forces on-time arrival at the required TPI conditions and the delta-v required for TPI is about 20.8 ft/sec in all cases. The Kepler corrected actual trajectory is close to the reference trajectory at every maneuver point with the result that the delta-v's differ from the reference trajectory by less than a couple of feet/second. Therefore, no data are given for the corrected actual trajectory.

In Table 6 it is seen that the total delta-v's required for the uncorrected actual trajectories also differ very little from the reference trajectories. The lack of a delta-v penalty is, however, somewhat illusory since when the effects of navigation and maneuver execution errors are considered, a real delta-v penalty can result for the uncorrected case, and not for the corrected case. The M=8 average phasing case illustrates the potential delta-v penalty problem. In Table 2 it is seen that the NC1 delta-v solution is too small, and hence the catch-up rate will be too fast. From Table 3 it is seen that the relative NC2

M	ERROR IN POSITION AT NCC EVENT (Relative position of Actual Trajectory - Relative position of Reference Trajectory)			
	With Correction for Keplerian Proprogation		Without Correction for Keplerian Proprogation	
	Error in Differential Altitude (nm)	Error in Downrange Distance (nm)	Error in Differential Altitude (nm)	Error in Downrange Distance (nm)
4, 5, 6, 7	+0.1	-1.2	7.3	-7.7
8	-1.3	1.5	8.5	-21.8
9	-2.8	4.4	5.0	-15.0
10	-3.7	6.2	5.8	5.4
11	-3.2	5.5	22.8	37.7
12	-2.0	3.1	42.6	75.9
13	0.2	0.1	59.8	107.3
14	1.0	-2.3	79.3	124.1
15	1.5	-2.1	66.9	120.7
16	1.0	-2.3	51.2	91.5

TABLE 5. Error in Relative Position at NCC Event

(Reference Trajectory 20 nm below and 120 nm behind)

M	Actual Trajectory Without Correction for Keplerian Propagation			Reference Trajectory*		
	Delta-v at NCC (ft/sec)	Delta-v at NSR (ft/sec)	Total Delta-v from NC1 to TPI (ft/sec)	Delta-v at NCC (ft/sec)	Delta-v at NSR (ft/sec)	Total Delta-v from NC1 to TPI (ft/sec)
4, 5, 6, 7	145.0	7.1	478.1	134.3	17.3	473.4
8	144.0	3.4	479.4	134.9	21.2	478.8
9	147.3	6.9	477.5	136.0	20.4	478.7
10	138.6	24.4	475.5	136.4	19.0	476.7
11	134.4	55.1	475.2	136.3	18.5	474.5
12	130.8	91.5	475.4	135.7	19.1	472.9
13	128.2	123.7	475.8	134.5	20.7	472.5
14	127.4	141.4	476.3	133.5	22.7	473.8
15	128.5	136.7	476.6	132.8	24.6	476.2
16	130.9	107.7	476.4	132.6	25.4	478.6

*The data for the actual trajectory with correction for Keplerian propagation agrees with the data for the reference trajectory to within a couple of feet/second, thus the actual trajectory data is not given.

TABLE 6. DELTA-V REQUIREMENTS AT NCC, AT NSR, AND FOR TOTAL PROFILE WITH AVERAGE PHASING CONDITIONS AT NC1

position is about 38 nm too close as compared to the relative NC2 position for the reference trajectory. Thus, the NC2 maneuver must decrease the catch-up rate with the result that the actual delta-v at NC2 is greater than that for the reference trajectory (Table 4).

The NC2 maneuver partially corrected the phasing error so that at NCC, the actual trajectory was only about 21 nm ahead of the reference trajectory (Table 5). However, the important thing is that while the reference trajectory is about 20 nm below the target orbit at NCC, the actual trajectory is only about 11.5 nm below. The coelliptic orbit is 10 nm below the target orbit. If NCC had occurred above the coelliptic orbit altitude, then NSR would be a retrograde maneuver and there would have been a delta-v penalty. Consequently, if navigation or execution errors at NC1 were such as to cause the NC1 maneuver to obtain an even faster catch-up rate (a smaller value of delta-v), then the downrange distance error at NC2 would be larger, the NC2 catch-up rate must be decreased still further, and NCC would then occur above the coelliptic orbit altitude. The extra delta-v required to raise the NCC maneuver point above the coelliptic orbit altitude, and the NSR retrograde delta-v represents the penalty.

Similarly, too large a delta-v at NC1 can result in a delta-v penalty by forcing NC2 to be a retrograde maneuver. However, as seen from the data, the margin for error is greater on the high side than on the low side. Six ft/sec too small reached the limit; however, 12 ft/sec too large still did not produce anywhere near an NC2 retrograde maneuver. Actually, too large a maneuver at NC1 will probably produce inefficient NCC and NSR maneuvers and thus, an increase in the delta-v cost before forcing NC2 to be a retrograde maneuver. This can be illustrated but first it is necessary to discuss two additional examples.

Tables 7 and 8 show the two additional examples of the delta-v requirements and the relative position errors at each maneuver point for uncorrected actual trajectories. The M=16 minimum phasing requirement and the M=13 maximum phasing cases have been selected as the examples because they involve the largest delta-v errors at NC1. As is the case with the average phasing requirement cases, the largest NC1 delta-v error results when the target vehicle is near zero latitude at the time of NC1.

As can be seen from Tables 6, 7, and 8, the total delta-v requirement from NC1 through TPI varies with the phasing requirements. This point was discussed previously and is due to the non-optimum NCC maneuver. However, the minimum phasing

Maneuver	REFERENCE TRAJECTORY			ACTUAL TRAJECTORY WITHOUT CORRECTION FOR KEPLERIAN PROPAGATION		
	Delta-v (Ft/Sec)	Distance Behind Target Vehicle (nm)	Distance Below Target Orbit (nm)	Delta-V (Ft/Sec)	Distance Behind Target Vehicle (nm)	Distance Below Target Orbit (nm)
NC1	234.6	4175	114.8	246.8	4175	114.8
NC2	166.9	210	21.1	28.8	557	14.0
NCC	20.0	115	18.9	19.8	260	97.0
NSR	18.0	49.5	10.0	153.2	49.5	10.0
TPI	20.7	18.6	10.0	20.8	18.6	10.0
TOTAL DELTA-V (FT/SEC)	460.2			469.4		

TABLE 7. REFERENCE TRAJECTORY AND ACTUAL TRAJECTORY CHARACTERISTIC FOR M=16 WITH MINIMUM PHASING CONDITIONS AT NC1.

Maneuver	REFERENCE TRAJECTORY			ACTUAL TRAJECTORY WITHOUT CORRECTION FOR KEPLERIAN PROPAGATION		
	Delta-V (Ft/Sec)	Distance Behind Target Vehicle (nm)	Distance Below Target Orbit (nm)	Delta-V (Ft/Sec)	Distance Behind Target Vehicle (nm)	Distance Below Target Orbit (nm)
NC1	22.8	8250	115.1	36.1	8256	115.1
NC2	167.3	495	140.4	72.8	720	132.9
NCC	250.8	124	22.1	245.7	214	74.9
NSR	25.8	49.5	10.0	114.5	49.5	10.0
TPI	20.8	18.7	10.0	20.8	18.7	10.0
TOTAL DELTA-V (FT/SEC)	487.5			489.9		

TABLE 8. REFERENCE TRAJECTORY AND ACTUAL TRAJECTORY CHARACTERISTICS FOR M=13 WITH MAXIMUM PHASING CONDITIONS AT NC1.

case of Table 7 further illustrates a delta-v penalty for the actual trajectory caused by too large a maneuver at NC1 and the use of the NCC maneuver. In this example the NC2 point is higher than for the reference trajectory, thus NCC will be at a lower altitude than for the reference trajectory. The result is a delta-v penalty of about 10 ft/sec. However, it should be noted that the total delta-v required for the minimum phasing (with a penalty) example is still less than the total detla-v required for the maximum phasing case.

Table 7 also illustrates a third potential delta-v penalty threat caused by too large a delta-v at NC1. The threat is that NC1 raises the altitude of NC2 above the coelliptic orbit altitude. This is most likely to happen for the minimum phasing cases since the reference NC2 altitude is only 10 nm below the coelliptic orbit altitude and the upper limit on delta-v error at NC1 is about 17 ft/sec before this type of penalty would result. Furthermore, since the delta-v budget must provide for the maximum phasing case, this type of penalty would probably not be a problem.

The corrected actual trajectories for minimum and maximum phasing conditions at NC1 were run for all M numbers, and these agreed with their respective reference trajectories to the same degree as for the average phasing condition cases given herein.

VI. Conclusions

The conclusions of this study are:

1. The modified CSI targeting method produces excellent solutions for the NC1 and NC2 maneuvers when compared to the solutions obtained by the conic NC/NH/NSR targeting method. The delta-v differences were generally on the order of 0.5 ft/sec, and no test case had a difference greater than one ft/sec. This means that the approximations used in the modified CSI method are adequate for the Skylab rendezvous.

2. Conic targeting with the correction for Keplerian propagation produced excellent solutions for the NC1 and NC2 maneuvers when compared to the precision integrated solutions. The delta-v differences were generally less than one ft/sec.

3. The NC1 maneuver in-plane delta-v can be in error by several ft/sec on either side of the ideal solution with no appreciable affect on the total delta-v required for rendezvous. (Within this range, the small change to the

total delta-v is caused by the second order effects of the non-optimum NCC-NSR transfer.) Outside the range, one or more of the subsequent maneuvers will be retrograde and a significant delta-v penalty is possible. The conic targeting methods without the correction for Keplerian propagation produce NC1 delta-v solutions ranging from 6. ft/sec too small to about 13.5 ft/sec too large over the range of M numbers considered. These extreme values are near the edge of, but within, the no delta-v penalty range. Note that this is not a statistical spread. A particular biased solution will result from a particular phasing situation. It would be better practice, however, to use this range to absorb the effects of navigation and execution errors at NC1. A biased targeting solution, together with expected navigation and execution errors, is likely to result in NC1 solutions outside the no penalty range.

4. An NC1 solution which is larger than the ideal solution causes the active vehicle to be further behind the target at NC2 and at NCC. This results in an increase in the slant range during the NC2 to NCC phase, so great, in some cases, that VHF tracking is not possible prior to the NCC maneuver.

VII. Recommendation

It is recommended that a correction for Keplerian propagation be incorporated for the Skylab CSM on-board targeting routine for the NC1 maneuver. Otherwise, the targeting bias errors can result in a significant decrease (or even entire elimination) of pre-NCC on-board navigation and, together with navigation and execution errors, can result in retrograde (hence, fuel wasting) maneuvers.

C. O. Guffee Jr.

C. O. Guffee

R. C. Purkey

$1025-\frac{COG}{RCP}-li$

R. C. Purkey

REFERENCES

1. Austin, W. L., Skylab-2 Launch Opportunities and Time in Coelliptic Orbit - Case 610, Bellcomm Memorandum for File, March 31, 1970.

2. AAP Spacecraft Software Configuration Control Board (SCB) Approved Program Change Requests (PCR's), MSC Memorandum 70-FS55-62, March 17, 1970.

3. Guffee, C. O., Purkey, R. C., A Study of the Phasing Capability of Apollo CSI/CDH Coelliptic Rendezvous Targeting Routines for AAP - Case 610, Bellcomm Memorandum for File, February 19, 1970.

4. Guidance System Operation Plan for Manned CM Earth Orbital and Lunar Missions Using Program Colossus 2E (GSOP), Section 5, Guidance Equation (Rev. 10), MIT, March 1970.

5. Guffee, C. O., Purkey, R. C., NAGS Documentation: A Computer Routine for Targeting the NC/NH/NSR Rendezvous Profile - Case 610, Bellcomm Memorandum for File, September 30, 1970.

6. Guffee, C. O., Purkey, R. C., NAGS Documentation: The NCC/NSR Rendezvous Maneuver Targeting Routine - Case 610, Bellcomm Memorandum for File, August 18, 1970.

7. Guffee, C. O., Purkey, R. C., Investigation of the Skylab Rendezvous Profile with Consideration to the VHF Tracking Coverage - Case 610, Bellcomm Memorandum for File, April 23, 1970.

8. Guffee, C. O., Purkey, R. C., Correcting Targeting Routines for the Errors due to Conic Approximations, Bellcomm Memorandum for File, In preparation.

BELLCOMM, INC.

Subject: Study of the MSC Proposed NC1/NC2 Targeting Routine for Skylab Rendezvous - Case 610

From: C. O. Guffee
R. C. Purkey

Distribution List

NASA Headquarters

H. Cohen/MLR
J. H. Disher/MLD
W. B. Evans/MLO
J. P. Field, Jr./MLP
T. E. Hanes/MLA
T. A. Keegan/MTE
A. S. Lyman/MR
M. Savage/MLT
W. C. Schneider/ML

MSC

M. Contella/CF24
P. C. Kramer/CF24
E. C. Lineberry/FM6
R. R. Reglebrugge/FM6
H. W. Tindall/FM

MIT/CSDL

S. Copps
G. STubbs

Bellcomm

A. P. Boysen
J. P. Downs
D. R. Hagner
W. G. Heffron
J. J. Hibbert
J. Z. Menard
I. M. Ross
P. F. Sennewald
R. V. Sperry
J. W. Timko
R. L. Wagner
M. P. Wilson
Division 101 Supervision
All Members Division 102
Department 1024 File
Central Files
Library